Single Photons from S + Au Collisions at the CERN Super Proton Synchrotron and the Quark-Hadron Phase Transition

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The preliminary results for the single-photon spectrum obtained by the WA80 collaboration are analyzed. The data are well described by a scenario where a thermalized quark-gluon plasma is formed initially, which expands, cools, hadronizes, and undergoes a freeze-out. It is also seen that the data do not seem to favor the scenario where the matter is initially formed in a hot hadronic phase, which cools and undergoes freeze-out and does not involve a phase transition.

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Relativistic heavy-ion physics is poised for a clean experimental verification of one of the most spectacular predictions of QCD—the existence of the quark-gluon plasma (QGP)—in the near future. Enhanced production of strange mesons, a suppression of J/ψ production, and production of thermal photons and dileptons are some of the most plausible signatures of the quark-hadron phase transition. Of these, the thermal photons and dileptons are believed to be *carriers of pristine information about the QCP* and also the subsequent hot hadronic matter, as they do not suffer any final state interaction. In addition their production cross section is a strongly increasing function of temperature, which leads to their copious production just when the matter is at its hottest and most dense stage.

Often it is not realized that even though a hot and dense hadronic matter may lead to a J/ψ suppression or a strangeness enhancement to the same extent as that for a QGP with a similar entropy density, the corresponding temperatures of the two phases would be quite different. This difference in temperature should lead to a quite different production of thermal photons.

In the present work we show that the first statistically significant (preliminary) data on *single* photon production from the WA80 experiment for the 200A GeV S + Au collisions [1] at the CERN Super Proton Synchrotron (SPS) enable us to make just this distinction and seem to rule out a scenario which does not involve a QCD phase transition.

We consider central collisions of the S + Au system and assume an interacting system having an initial transverse radius R_T equal to the radius of the sulphur nucleus and a $dN_{\text{charge}}/dy = 150$ at $y = 0$. Assuming an isentropic expansion one can relate the particle rapidity density $dN/dy \approx 1.5 \times dN_{\text{charge}}/dy$, the initial temperature (T_i), and the initial time (τ_i) as [2]

$$T_i^3\tau_i = \frac{2\pi^4}{45\zeta(3)\pi R_T^2 4a_k}\frac{dN}{dy}, \quad (1)$$

where $a_k = a_Q = 37\pi^2/90$ if the system is initially in the QGP phase, consisting of (massless) u and d quarks and gluons. If, however, the system is initially in a hadronic phase, consisting of π, ρ, ω, and η mesons, we have $a_k = a_H \approx 4.6\pi^2/90$ [3,4] appropriate for temperatures in the range 100–400 MeV. For the initial time τ_i we take the canonical value of 1 fm/c and also (perhaps) the more realistic value of $\tau_i \approx 1/3T_i$ [3–7] implying a more rapid thermalization.

Thus, if the system is formed in the QGP phase at $\tau_i = 1$ fm/c, we have $T_i = 203.4$ MeV. If however, we take $\tau_i = 1/3T_i$, we get $\tau_i = 0.184$ fm/c and $T_i = 357.6$ MeV.

On the other hand, if we assume the system is produced in the hot hadronic phase, with the same entropy density as before at $\tau_i = 1$ fm/c, we get $T_i = 407.8$ MeV. We have not considered the other extreme of $\tau_i = 1/3T_i$ for the hadronic matter as it implies an enormously high initial temperature of 1015 MeV, where the picture of noninteracting hadrons will break down, and also because it implies a thermalization time which is a very small fraction of the time taken by the two nuclei to cross each other which is unphysical.

Thus we consider two different scenarios. In the *first* scenario we assume the matter to be formed in a QGP phase at the initial time τ_i and initial temperature T_i, which then expands and cools and goes into the mixed phase at the transition temperature $T = T_c$. When all of the quark matter has adiabatically converted into hadronic matter, it cools again and undergoes a freeze-out at $T = T_f$.

In the *second* scenario we consider the system to be formed in a hadronic phase with the same entropy density as before [4], at the initial time τ_i, and an initial temperature T_i which expands, cools, and undergoes a freeze-out at T_f, *without admitting a QCD phase transition.*

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We assume a boost-invariant hydrodynamic expansion both without [8] and with transverse expansion of the system Refs. [7,9].

The thermal photon spectrum is obtained by convoluting the rate of emission of photons with the space-time evolution of the system, using methods which are well established by now [3,6,7]. For emission of photons from the QGP we consider the Compton plus annihilation contribution corrected for infrared divergences as [10],

$$E\frac{dR}{d^3p} = \frac{5}{9}\frac{\alpha\alpha_s}{2\pi^2}T^2 e^{-E/T}\ln\left[1 + \frac{2.912E}{g^2T}\right], \qquad (2)$$

where α_s is the strong coupling constant [11]. For the hadronic matter we explicitly consider all the reactions involving the complete list of (nonstrange) light mesons ($\pi\pi \rightarrow \rho\gamma$, $\pi\rho \rightarrow \pi\gamma$, $\pi\pi \rightarrow \eta\gamma$, $\pi\eta \rightarrow \pi\gamma$, and $\pi^+\pi^- \rightarrow \gamma\gamma$) and the decay of vector mesons ($\omega^0 \rightarrow \pi^0\gamma$ and $\rho^0 \rightarrow \pi^+\pi^-\gamma$) considered by Kapusta, Lichard, and Seibert [10] (see also [4]). In addition, we include the contribution of $\pi\rho \rightarrow A_1\gamma$ through the parametrization suggested by Xiong, Shuryak, and Brown [12] whose results are rather similar to those of Song [13].

The photon spectrum is then obtained as

$$\frac{dN}{d^2p_T dy} = \int\left[f_Q(r,\tau,\eta)\left(\frac{EdR}{d^3p}\right)_{\rm QGP} + f_H(r,\tau,\eta)\left(\frac{EdR}{d^3p}\right)_{\rm Had}\right]\tau\, d\tau\, r\, dr\, d\eta\, d\phi\,, \qquad (3)$$

where f_Q is the fraction of the quark matter in the system and f_H is the hadronic fraction [14]. The differential cross section is then obtained by multiplying the above result by $\sigma_{\rm in} = 900$ mb, the inclusive cross section appropriate for the data considered below [15]. We take $T_c = 160$ MeV and assume the freeze-out to take place at 100 MeV. In any case the thermal photon production becomes insignificant at lower temperatures.

In Fig. 1 we present our results for thermal photons for $\tau_i = 1$ fm/c, with transverse expansion. Switching off the transverse expansion enhances the lifetime of the system and also eliminates the transverse kick received by the particles produced during the later stages of the evolution. Upon comparison with a calculation involving a purely longitudinal expansion, the transverse expansion effects were found to lead to only marginal differences. This is not unexpected at SPS energies for such a small system, though the situation is likely to change at higher energies attainable at the BNL Relativistic Heavy Ion Collidor and CERN Large Hadron Collider. All the results shown here, however, are obtained by accounting for the transverse expansion of the system to eliminate any uncertainty on this account. The quark matter contribution (i.e., the sum of the contributions of the QGP phase and the QGP fraction of the mixed phase) is shown separately. It is seen to be of the order of 2%–3% of the total contribution from all of the hadronic reactions mentioned above, including the $\pi\rho \rightarrow A_1\gamma$ reaction. A near quantitative description of the data is obtained without any normalization and without any arbitrary free parameter. The results are quite sensitive to the transition temperature, since most of the contribution comes from the mixed phase. We have additionally shown the total contribution for $T_c = 150$ and 170 MeV to illustrate this point. It is likely that a nonzero chemical potential may alter the critical temperature to some extent, and it is hoped that the range of the critical temperatures considered here encompasses this uncertainty.

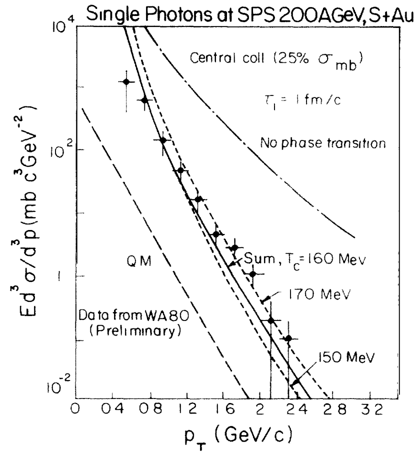

FIG. 1. Single photons from central collisions of S + Au system obtained by WA80 collaboration [1] (preliminary). The dashed curve gives the contribution of the quark matter in the QGP and the mixed phase. The solid curve gives the sum of all the single photons from the quark matter and the near exhaustive list of hadronic reactions involving (nonstrange) light mesons and vector decays. The $\pi\rho \rightarrow A_1\gamma$ contribution is also included. The system is assumed to be initially produced in QGP at $\tau_i = 1$ fm/c, which then expands, cools, and undergoes a hadronization in a first order phase transition and then freeze-out. The critical temperature is taken as 160 MeV, and the transverse expansion of the system is explicitly accounted for. The long-dash-dotted curve gives the results for a *no phase transition* scenario, where the system is formed in a hot hadronic phase, expands, cools and undergoes a freeze-out. Results for $T_c = 150$ and 170 MeV are also given for a comparison.

It is gratifying to see that the picture, perfected over the past many years [16], of a thermalized QGP produced in a relativistic nucleus-nucleus collision undergoing expansion, cooling, and hadronization in a first order phase transition provides such a quantitative description to the data. It is also quite striking that the data seem to clearly indicate that a scenario which does not involve a quark-hadron phase transition is unlikely (see Fig. 1).

Finally in Fig. 2, we give our results for the more optimistic (and perhaps more realistic) initial temperature obtained by taking $\tau_i = 1/3T_i$ in the QGP scenario. Now we see that the larger initial temperature enhances the quark-matter contribution to 3%–10% and in fact improves the description of the data considerably. We

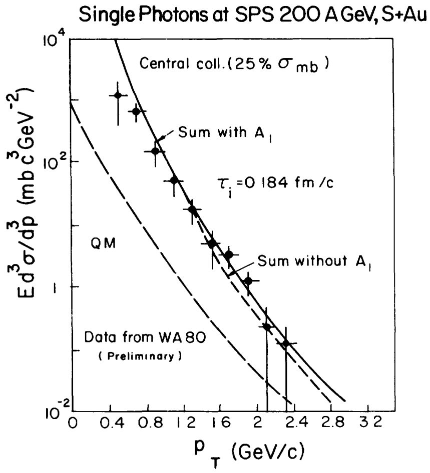

FIG. 2. Same as Fig. 1, with the formation time $\tau_i = 1.3T_i$, where T_i is the initial temperature of the QGP. The short-dashed curve gives the total contribution without the contribution of $\pi\rho \rightarrow A_1\gamma$ reaction. The critical temperature is taken as 160 MeV.

also show the results without the contribution of the much discussed $\pi\rho \rightarrow A_1\gamma$ reaction. This reaction is seen to contribute up to 25% at larger transverse momenta.

Before summarizing let us briefly examine some of the input assumptions. First, all the hadronic reactions are evaluated by using the masses, decay widths, etc. of the mesons as expected at $T = 0$. Even though it is expected that these quantities may be temperature dependent, the present estimates on these variations have their largest uncertainty just around the critical temperature. Still, any decrease in the masses of the light mesons considered here will enhance the hadronic matter contribution to the single photons. The hydrodynamic model used here is based on simplest assumptions and should be valid at least for the central rapidity region discussed here. The adiabatic phase transition assumed here implies that the hadronization is much more rapid than the cooling. In absence of this, we should have a supercooled mixed phase [17] from which the emission of photons may be reduced. This effect, however, is not much more than 10%–15% [18]. All the calculations reported in this work have been performed by neglecting the baryonic chemical potential. We note however that for the central rapidities considered here, the baryonic rapidity density $dN_{\mathrm{B}-\bar{\mathrm{B}}}/dy \approx 22$ [19] whereas the particle rapidity density is 225, implying a very small number of net-baryons compared to the total number of secondaries. As mentioned earlier, the presence of baryons will perhaps lower the critical temperature. However, the inclusion of baryons will also imply an increase in photon producing processes in the hadronic matter, and thus we feel that the final outcome will not be altered significantly. Finally, we have not included the strange mesons (say, K mesons etc.) for the following reasons. Firstly, the hadronic matter as considered by us is consistent with the QGP which is composed of u and d quarks and gluons and for which a fairly exhaustive list of reactions have been considered in literature [4,10,12,13]. Secondly, we feel that, as before, while the addition of strange mesons will lower the temperature by about 10%–12% [20], the contribution of photon producing reactions [22] will increase. Thus the difference between the no-phase transition scenario and the QGP scenario will remain essentially unaltered.

In conclusion, we have analyzed the preliminary WA80 single-photon data for central collisions of sulphur and gold nuclei at SPS energies. The data are well described by assuming that a thermalized quark-gluon plasma is formed in the collision, which then cools due to expansion and hadronizes before undergoing a freeze-out, a picture which has been in vogue for quite some time. The theory does not involve any arbitrary free parameter and no normalization factor is required. Inclusion of a near exhaustive list of reactions involving light mesons is seen to be important for a quantitative description of the results. On the other hand, a scenario which does not incorporate a quark-hadron phase transition does not seem to be favored by the data. The feasibility of such a clear distinction between the two scenarios using single photons is but one of the many notable outcomes of the data which have only now become available due to the painstaking analyses performed by the WA80 group.

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